

THE FIREPLUME MODEL: TOOL FOR EVENTUAL APPLICATION TO PRESCRIBED BURNS AND WILDLAND FIRES

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ABSTRACT

Land managers are increasingly implementing strategies that employ the use of fire in prescribed burns to sustain ecosystems and plan to sustain the rate of increase in its use over the next five years. In planning and executing expanded use of fire in wildland treatment, it is important to estimate the human health and safety consequences, property damage, and the extent of visibility degradation from the resulting conflagration-pyrolysis generated gases soot and smoke during flaming, smoldering and/or glowing fires. Traditional approaches have often employed the analysis of weather observations and forecasts to determine whether a prescribed burn will affect populations, property, or protected Class I areas. However, the complexity of the problem lends itself to advanced PC based models that are simple to use for both calculating the emissions from the burning of wildland fuels and the downwind dispersion of smoke and other products of pyrolysis, distillation and/or fuels combustion. These models will need to address the effects of residual smoldering combustion, including plume dynamics and optical effects. In this paper, we discuss a suite of tools that can be applied for downwind dispersion component problem. These tools include the dispersion models FIREPLUME and SMOKE, together with the meteorological preprocessor SEBMET.

Keywords: smoldering combustion, prescribed burns, fire modeling, FIREPLUME, air quality, wildland fires, plume rise, Monte Carlo, SMOKE, dispersion model, Lagrangian, smoke management plans, EPM

BACKGROUND

A Federal Wildland Management Policy and Program Review was conducted in 1995 in response to the notable increase in unplanned fires occurring in 1987-1991 and 1995 (over 100,000 events),* and the underlying unhealthy condition of our public wildlands (DOI/DOA, 1995). The review findings and recommended actions lead to the fostering of interagency cooperation (five agencies) on wildfire management and an agreement on the need for several changes to existing fire and land management practices (DOI/DOA, 1996). Recommendations were made to renew emphasis on use of fire into Federal land management programs in "an ongoing and systematic manner, consistent with public health and the environment." In 1997, the cooperating agencies began actions to facilitate the implementation of landscape-scale prescribed burns across agency boundaries in the most vulnerable wildlands as means to achieve reduction in unnatural fuel densities that contribute to increasing wildland fire hazards.** Annual prescribed burn treatment targets are projected to increase to about 1.9 to 3.4 million acres per year ($\sim 7.7 \times 10^5$ and $\sim 1.4 \times 10^6$ ha/yr., respectively) by 2002 and 2005, respectively (Hilbruner, 1999). Although these targets are intended to aid in the overall reduction of the current fire hazard and restore wildland ecosystems to their healthy state, a recent study has raised questions about the utility of broad-based fire suppression and prescribed burns, sometimes together with mechanical treatment, to imitate natural fire regimes (Keeley, J., et al. 1999). They found that the occurrence of larger more intense catastrophic wildfires in brush covered regions of California have been

* In the U. S. over the past decade, a significant increase has occurred in burned wildfire area. In 1995, a record number, about 130,000 of wildfires occurred, burning roughly 2×10^6 acres ($\sim 8.1 \times 10^5$ ha). Efforts have also increased to completely suppress fires.

** About 1 million-acres ($\sim 4 \times 10^5$ ha) were fire treated in 1997, almost doubling the treatment from the previous year and nearly quadrupling the 1992 prescribed burns (Hilbruner, 1999).

intensified by past fire suppression and that prescribed rotational burning programs are not likely to be successful in eliminating these events. It is important to note the generally held belief that fire suppression measures have contributed to larger more intense and increasingly destructive shrubland wildfires. Keeley, et al. concludes that the key drivers of the California brush-land fires are high autumn föehn winds and an increasingly encroaching urban-wildland interface, and that the most effective prevention strategy would be to establish strategically located urban-wildland buffer zones for targeting more intensive fuel management. This is consistent with the Conrad and Weise's (1998) recommended two part strategy to establish: "... 1) strategically placed dynamic fuel management zones in wildland areas to provide access and opportunities for control, and 2) intensive fire risk management zones ... to protect values in the wildland-urban interface."

Some are saying that the above findings may raise a new fire schism as it pertains to the utility broad-based fire suppression as an integrated fire management philosophy. However, the currently planned national projections of prescribed burn usage are not likely to be significantly altered (Hilbruner 1999). If these projections are foreseen, land and air quality managers could be faced with significant public health/welfare and safety issues from smoke and hazardous air pollutants generated from prescribed burning. The health standard issue has been clouded by a heated debate on establishing a science-policy definition of "natural" background visibility for assessment of regional haze impacts and the analysis of emission tradeoffs between wildfires and prescribed burns. In recognition of this and other issues, the U. S. Environmental Protection Agency (EPA) worked in partnership with Federal land managers, including the Departments of Agriculture, Interior and Defense, and State and tribal air and land management agencies to develop and issue the Interim Air Quality Policy on Wildland and Prescribed Fires (EPA, 1998). The interim national policy was developed in coordination with the Subcommittee on Ozone, Particulate Matter, and Regional Haze Implementation Program formed under the auspices of the Federal Advisory Committee Act (FACA). It urges air quality managers to minimize impacts of wildfire smoke and provides incentives to States or Tribes to adopt and implement smoke management plans. The plans are required to cover smoke control measures, monitoring, and public notification/awareness. In addition to identifying the need for safety and contingency plans

addressing smoke intrusion, other important smoke control components are also highlighted in the management plans. These include a requirement that the central air quality review authority evaluate smoke dispersion conditions and estimate impacts to sensitive receptor areas, including identification of distance and direction of impacts from the burn site. It also requires that fire prescriptions submitted prior to the day of the planned burn specify minimum requirements for smoke dispersion (e.g., minimum surface and upper level winds, and mixing heights). The interim policy will be finalized with careful considerations of the implications from the recently published Regional Haze Rule (July 1, 1999, FR 35713-35774) and from discussions with a special Department of Agriculture task force on agricultural burning. An addendum to the interim national policy addressing agricultural burning is expected in the fall of 1999, with a final policy that addresses regional haze issues by the end of year 2000 (Woodard, K. 1999). Although EPA acknowledges that the policy does not establish a binding norm, they state that it does or may have current regulatory State Implementation Plan implications. This includes compliance with the health and welfare air quality standards (e.g., NAAQS), general Clean Air Act "conformity" requirements, and the new source review rules (e.g., PSD*). The regional haze rule, upon settlement of implementation issues, could play a significant role in shaping future smoke management policy.

In addition to EPA's wildfire/air quality policy initiative, related efforts are being carried out by the Western Regional Air Partnership (WRAP), formed in order to implement the recommendations from the Grand Canyon Visibility Transport Commission (GCVTC, 1996). Since eight of the GCVTC's recommendations were specific to wildland fires, the WRAP established a Fire Emission Joint Forum to assist in addressing the Commission's wildfire-related visibility issues. The forum's charge is to recommend improved methods or models for estimating smoke emissions and air quality impacts from wildland fires, and develop a fire emission data set and tracking system (WRAP, 1999). These efforts are intended to lead to recommended strategies and methods to manage fire emissions and control regional haze in the GCVTC covered western states.

A number of the common regulatory compliance objectives and goals inherent to the above mentioned

* An interagency working group (NFS, NPS, FWS), known as FLAG (Federal Land Managers AQRV Work Group) was formed in 1997 with the goal to "achieve greater consistency in procedures each agency uses in identifying and evaluating AQRV." The FLAG intends to issue draft guidance in the FR (before end of FY 99) on new methods and procedures aimed at assessing impacts to Class I PSD areas.

wildfire smoke mitigation/prevention initiatives will require in some cases the development and use of specialized modeling tools and/or data systems. For example, emissions from the smoldering or residual smoldering combustion (RSC)* of biomass fires may pose the largest inhalation exposure risk to nearby residents and firefighters, especially those involved in mop-up operations. This is due to the combination of lower plume buoyancy and differences in chemical composition compared to a flaming fire, for example. Fuel conditions (e.g., wet/dry) and weather (e.g., wind/rain) are some of the variables affecting the relative production of flaming and RSC generated compounds. None of the currently used fuel consumption (e.g., FOFEM, BURNUP), smoke emission (i.e., EPM) or smoke dispersion models (e.g., NSFpuff, VSMOKE, TSARS) are able to characterize the RSC component of these fires, which under drought conditions can account for over 50% of the total biomass burned. In addition to smoke, smoldering fires produce toxic smoke condensates, some of which are known or suspected carcinogens (McKenzie, L. et al. 1995). At least three compounds from RSC of various fuels produce toxic chemical compounds that are also listed as hazardous air pollutants by U. S. EPA. Preliminary evidence exists that during the RSC, the gaseous composition of smoke changes significantly and proportionately smaller particles are produced. Although emissions related to the production of respirable aerosols ($PM_{2.5}$) during RSC have been measured in the field. Emission factors have been derived from these ground-based measurements (Ward, 1988), but significant uncertainties still exist about initial smoke production rates, composition, and growth mechanisms (Yokelson, et al. 1997b). However, further laboratory experiments are currently being conducted using filters and portable remote sensors (i.e., Fourier transform infrared spectroscopy) to measure fluxes of $PM_{2.5}$ and along with the gaseous combustion generated components (see Yokelson, R, et al., 1999, published in these proceedings).

Earlier this year the Forest Service issued a technical National Strategic Plan on modeling and data required for managing air quality impacts from planned and unplanned wildland fires (Sandberg, et al., 1999). Its principal intent is to serve as a technical reference to the teams involved in smoke management policy development and to those who will manage the development and application of models and data for wildland fire air quality policy implementation. The plan, com-

monly referred to as the "Air Quality Express," recommends nine strategies to assist land and air quality managers in dealing with wildland fire and air quality issues. The strategies cover research and development needs and implementation goals for characterizing and estimating wildfire source strength, air quality assessments (i.e., source-receptor impact linkages), and effects on receptors. It also calls for the development of a readily available national database system and a means for timely and effective public advisories/notifications.

This paper describes a set of tools for smoke and fire modeling that can be used for assessing air quality impacts from wildfires. Background is provided on the experimental and empirical development of the codes, along with the theoretical formulation and model validation. Each of the model's distinguishing capabilities and attributes are covered along with a couple of brief examples of historical applications. A wildland fire-modeling framework is proposed to address some of the modeling-data needs and goals identified in the Forest Service's National Strategic Plan, including the need to address regional haze/plume blight issues. Finally, future air quality model development and end-user needs are covered in anticipation of the regulatory compliance implications of EPA's final wildland fire policy initiative and the current efforts to manage fire emissions in concert with the protection of Air Quality Related Values.

MODEL DEVELOPMENT OVERVIEW

The SMOKE and FIREPLUME models were developed to simulate atmospheric dispersion and air quality impacts from fires and other smoke sources (i.e., U.S. Army smoke generators). In this section, we discuss the development of these models while highlighting their relevance particular attributes to the prescribed burn problem. We start our discussion with FIREPLUME, followed by the SMOKE model. The intent here is to lay a foundation illustrating that, with some further limited development, these models can be combined (together with the SEBMET meteorological preprocessor) to provide an integrated fire-smoke dispersion tool for assessing the impacts from wildland fires.

The FIREPLUME model predicts the ground-level concentration field resulting from chemicals emitted

* "Smoldering combustion" can be defined as a complex mix of small flames, fuel pyrolysis (thermal decomposition of fuel), and glowing combustion of char. It typically produces a white aerosols predominantly generated from pyrolysis products (e.g., formaldehyde, phenol, organic acids) and/or non-visible secondary NH_3 aerosol and CH_4 from glowing combustion. During flaming combustion black smoke of carbonaceous aerosols and other highly oxidized compounds are produced (Yokelson, et al. 1997a).

from or within (1) instantaneously discharged thermals or explosive discharges, (2) fires that generate hot continuous plumes or (3) smoldering or decaying fires. FIREPLUME also treats passive or neutrally buoyant releases, which serve as a limiting case for a smoldering fire. FIREPLUME consists of two components. The first is a stochastic Lagrangian dispersion model that estimates the vertical dispersion of both buoyant and non-buoyant releases in the atmospheric boundary layer. In the following discussions, this component is referred to as MCLDM (Monte Carlo Lagrangian Dispersion Model). The second component is a puff dispersion model that treats horizontal dispersion and transient emissions from the source. Taken together, these components provide the time varying concentration fields resulting from releases in which both the buoyancy and chemical release rate vary with time.

The FIREPLUME model is an extension of a Lagrangian particle model (MCLDM) developed over the past 10 years. This model was originally conceived to predict three dimensional concentration fields arising from releases of military obscurants (fog oil and hexachloroethane) and was motivated by the desire to correctly represent dispersion phenomena observed during experimental studies. Since atmospheric dispersion models available at that time did not adequately account for the turbulent structure of the convective boundary layer, development of the Lagrangian model began with a study of convective conditions (Liljegren et al. 1989). The Lagrangian model developed for that application compared very well with field data available at the time. In particular, the rising centerline that occurs with plumes originating near the ground under convective conditions (e.g., water tank data by Willis and Deardorff 1974) was correctly represented by the Lagrangian particle model. Later work by Brown (1997) extended the model (MCLDM) to stable and near neutral conditions and refined it for modeling in the surface layer.

In 1996, the ability to treat buoyant plumes was added to MCLDM in support of an impact analysis for fires involving cylinders containing uranium hexafluoride (Brown et al. 1996). The framework for treating source buoyancy closely follows from the so-called Briggs's two-thirds law (see Briggs 1984), which is applicable in cases where the buoyant source has low initial momentum. Fires clearly fall into this category (Weil 1982). As discussed in the next section, the plume rise relationships are incorporated into MCLDM to provide a mean vertical velocity for the individual particles. The final or limiting rise of the particles was

established using published relationships for a variety of atmospheric conditions. Using this framework, the vertical dispersion from a variety of buoyant release scenarios can be evaluated, from intensely buoyant sources typical in actively burning forest fires to very low buoyancy sources, such as, in the residual stages of smoldering biomass.

At the same time, a puff dispersion "post processor" was added to MCLDM to (1) account for the horizontal dispersion of the plume and (2) translate the vertical dispersion estimates of MCLDM to ground level concentrations for scenarios involving a time dependent release. MCLDM together with the puff dispersion post processor became the FIREPLUME model.

The SMOKE model is a PC based puff dispersion model for predicting the transport of fog-oil smoke plumes produced in US Army training exercises. The SMOKE model was developed using dispersion data from several field studies employing smoke generators or tracer releases (e.g., SF₆) together with results of the Lagrangian particle model used within FIREPLUME. There were two primary field studies carried out in support of the SMOKE model development. These experiments are the AMADEUS and the Atterbury-87 experiments, which are briefly described below.

The AMADEUS experiments were conducted in September and October 1987 (DeVaull, et al. 1990, Brown, et al. 1990). The site for this study was located 22 km northeast of Red Bluff, California in a moderately complex terrain site along a creek valley. Through most of the test area, the valley was 300 m wide and 150 m deep (valley floor to main ridge). The AMADEUS study was part of a mesoscale wind field study (Project WIND) jointly organized by the US Army Atmospheric Sciences Laboratory and the US Forest Service. To take advantage the diurnal wind direction characteristics in the valley, two smoke release locations and associated sampling grids were established. For daytime trials, smoke was sampled at several transects 25 m to 250 m from the source. For the nighttime trials, smoke was sampled at several transects 25 m to 3,200 m from the source. The trials ranged from 12 to 67 minutes in duration with the majority of the releases lasting between 30 min. and an hour. Fog-oil aerosol concentrations were sampled at heights of 2 and 8 m using aspirated filter samplers. Real-time smoke concentrations were also recorded at a height of 2 m using an optical device. In addition, over 250 aerial photographs of the smoke plumes were taken during all but the nighttime smoke releases (see Figure 1). Since this study was conducted as part of Project WIND, the

meteorology at the site was very well characterized with measurements from a variety of weather instruments. Altogether, 12 fog-oil trials were conducted: seven during stable meteorological conditions and five during unstable conditions.

The Atterbury-87 experiments were conducted in a tall grass prairie in south central Indiana in November 1987 (Liljegren, et al. 1989, DeVaul, et al. 1990). The test area was a large tall-grass meadow surrounded on three sides by hills 25 to 50 m high. The immediate test area was relatively flat with a moderate downward slope of between 1 and 2 % from northwest to southeast. The ground cover during the period of the study was roughly 1 m high and fairly uniform across the test area. The area surrounding the site was densely forested in all directions with deciduous trees 10 to 20 m tall. The terrain and vegetation features of the surroundings affected the surface turbulence structure as well as the wind field although the flat terrain and regular ground cover within the test area itself provided a nearly uniform flow. All smoke releases were at a height of approximately 1-2 m, and the duration of the smoke releases spanned from 25 min. to 76 min. Five of the tests employed HC (hexachloroethane) smoke released by "smoke pots," and the other four tests used fog-oil smoke released from a single M3A4 fog-oil smoke generator. Mean and real time fog-oil aerosol concentration was measured across several

transects spanning 50 m to 675 m from the release points. Meteorological parameters were measured at 5 levels on a 10-m tower near the center of the sampling grid.

As mentioned in the discussion of the FIREPLUME model, dispersion phenomena observed during these experiments initially led to the development of a Lagrangian particle model. However, for use in troop exercises involving obscuration, the military needed a faster running model that could be run on a PC in the field. Using the concentration data from the two mentioned experimental studies as well as published results from other studies, a semi-empirical integral dispersion model applicable to ground level sources was developed and adapted to a puff dispersion framework. In development of the integral model, a parametric analysis of dispersion estimates from MCLDM (see Brown 1997) was performed to allow extension to a wider range of conditions than are provided in the experimental data. The puff dispersion framework allowed other phenomena important to the problem to be more completely addressed while allowing the model to be put into a fast running PC form. Five issues particularly relevant to both fog-oil smoke dispersion and prescribed burns were closely examined and addressed in the model. These are: (a) convective liftoff of plumes generated from near-surface releases during strongly unstable conditions, (b) terrain and vegeta-

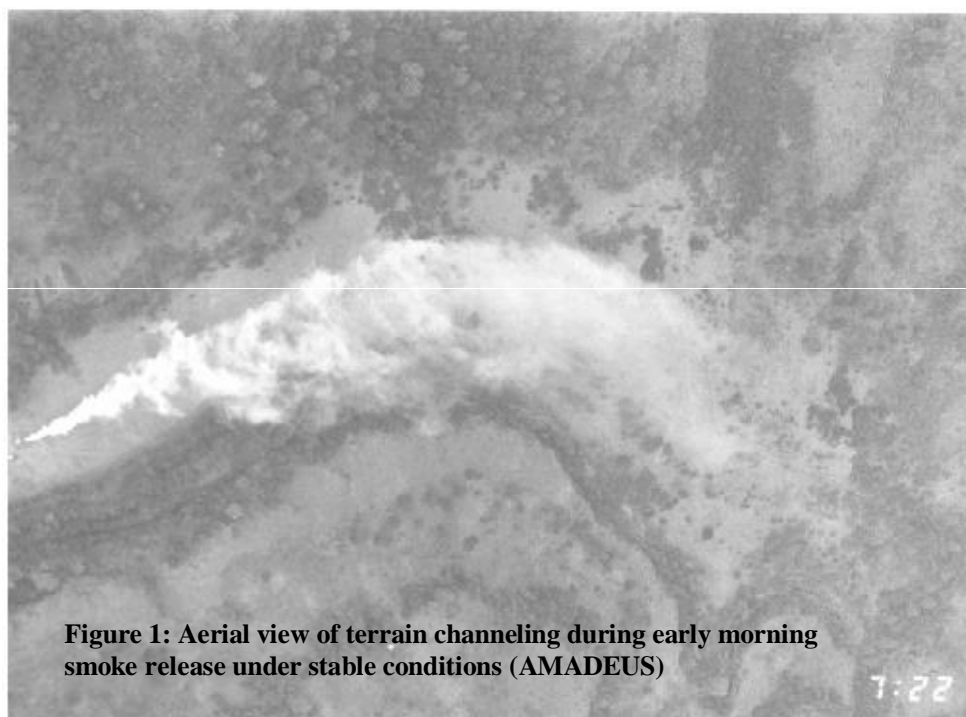


Figure 1: Aerial view of terrain channeling during early morning smoke release under stable conditions (AMADEUS)

tion effects on plume dispersion, (c) transitional meteorology, (d) the short duration of smoke releases and (e) the surface deposition of suspended smoke aerosol.

The remaining component of the SMOKE PC model that has not been discussed is the meteorological model SEBMET (Surface Energy Budget METeorological model). SEBMET estimates surface sensible and latent heating of the atmosphere, friction velocity and mixing height using routinely available meteorological data together with landcover characteristics which can be either user specified or defaulted to values from a national landcover database in the code. The estimation of atmospheric turbulence parameters is a critical component of the overall dispersion problem especially for buoyant releases, which depend strongly on the structure of the lower atmosphere. SEBMET is built from a detailed analysis of the energy budget at the surface of the Earth together with an integral model that predicts the growth of the daytime or convective boundary layer. It has recently been extended to include short-term forecasting and data estimation for missing or unknown observational data.

Since both SMOKE and FIREPLUME were developed under a common stochastic modeling framework, it would be a natural extension to couple the models for applications requiring the strengths of both models. This idea will be further explored later in the paper.

MODEL FORMULATION

In this section, we provide an overview of the formulation for the FIREPLUME and SMOKE models. Additional details can be found in the cited technical reports.

The core component of the FIREPLUME model is MCLDM, introduced in the previous section. In this model, the Lagrangian trajectories of a large number of particles are simulated to develop the mean concentration field directly from the probability density function of the particle positions. The particle trajectories are calculated using atmospheric boundary layer statistics as well as initial source buoyancy. To calculate particle trajectories, the Lagrangian model employs the Langevin equation, which provides a realistic physical description of particle behavior in a turbulent flowfield. Application of the Langevin equation to model turbulent motion takes advantage of the fact that time scales governing acceleration variations are much smaller than the time scales governing velocity variations. Indeed, for the atmospheric boundary layer, this

proves to be a very good assumption as illustrated in the photographic evidence of van Dop et al. (1985).

For one dimensional particle motion in the vertical direction, the Langevin equation reads:

$$\frac{dw}{dt} = -\frac{w}{T_L} + \xi(t) \quad (1)$$

where, w is a fluctuating velocity component, T_L is the Lagrangian time scale and $\xi(t)$ is a white noise random process. For homogeneous turbulence, integration of this stochastic differential equation provides the following Markov-chain relationship for the particle velocity,

$$w(t + \Delta t) = \left(1 - \frac{\Delta t}{T_L}\right) w(t) + \mu \quad (2)$$

$$\text{where, } \bar{\mu} = 0 \quad \text{and} \quad \overline{\mu^2} = \frac{2 \Delta t \sigma_w^2}{T_L}.$$

Here, μ is a random forcing function that is Gaussian for homogeneous turbulence. Reid (1979) and Ley (1982) have illustrated the applicability of the Langevin equation for modeling dispersion in the homogeneous neutral surface layer and have shown that predicted vertical distributions of particles (i.e., vertical concentration profiles) are in close agreement with experimental data.

The application of Langevin approach to model dispersion in vertically inhomogeneous turbulence, such as that seen in the convective boundary layer, is more complicated. Early investigators noted that the addition of a mean vertical velocity was necessary to prevent particles from clustering in regions of low vertical velocity variance or low Lagrangian time scale. Thomson (1984, 1987) further argued that additional moments of the random forcing function needed to be modified to prevent unphysical particle behavior. By requiring the steady state density function of the particle distribution to approach the density function of the air as specified by the Eulerian velocity moments, Thomson (1984) derived a general expression for relating the moments of μ to the Eulerian velocity field. Thomson's expressions include a mean vertical velocity, corrections to the variance of μ and expressions for higher order moments of μ . Liljegren et al. (1989) employed Thomson's approach to study dispersion in the convective boundary layer using Eulerian velocity moment data from both atmospheric and water tank studies. Concentration predictions from these studies agreed very well with water tank concentration data reported by Deardorff and Willis (1985) as well as at-

mospheric concentration data from the AMADEUS and Atterbury-87 field experiments previously discussed.

For application of MCLDM to near-neutral and stable conditions, statistics for these boundary layers as determined from several numerical and observational studies are also incorporated into the model. In addition, the lower boundary (i.e., the ground) is properly represented by incorporating the necessary turbulent statistics through the surface layer, including a realistic canopy layer. (see Kaimal and Finnigan [1994] for a discussion of in-canopy turbulence). Better estimates of near-ground concentrations, especially from low-level sources, are provided through improved treatment of the lower atmosphere turbulent structure, including the canopy layer. Brown (1997) illustrates the applicability of this model to unstable, near neutral and stable conditions through comparison to data from a variety of field studies.

To address continuous buoyant sources such as fire plumes, we use a representation of Brigg's two-thirds law since the initial momentum of a fire plume is insignificant in comparison with the plume buoyancy. Although Brigg's relationship is primarily used for stack emissions, its extension to fire buoyancy is straightforward. Expressed in terms of Froude number and velocity ratio K, and including virtual source effects, Brigg's two-thirds law reads:

$$\Delta h = \left(\left(\frac{3 r_o x^2}{4 \beta^2 F^2 K^3} \right) + \left(\frac{r_o}{\beta} \right)^3 \right)^{1/3} - \frac{r_o}{\beta}, \quad (3)$$

where Δh is the plume rise, x is the downwind distance, r_o is the fire radius [m], K is the velocity ratio ($K = U/w_o$), β is the entrainment coefficient and F is the Froude number. The Froude number is:

$$F = \left(\frac{w_o^2 \rho_a}{2 \Delta \rho r_o g} \right)^{1/2}, \quad (4)$$

where w_o is the initial vertical velocity [m/s], ρ is the air density [kg/m³] and $\Delta \rho$ is the initial density difference between ambient air and the fire plume.

Equation (3) can be used to predict fire plume rise in both stable and unstable conditions (i.e., into both positive and negative temperature gradients). Due to the effects of entrainment into the plume and thermal stratification of the atmosphere, however, the rise of the fire plume is limited. For stable conditions, plume rise is limited by thermal stratification. Based on a

survey of field data Briggs (1984) suggests that the final rise in stably stratified air is (in terms of F and K)

$$\Delta h_f = 2.1 \left(\frac{r_o U^2}{N^2 F^2 K^3} \right)^{1/3}, \quad (5)$$

where Δh_f is the final rise in [m] and N is the Brunt Vasaila frequency.

For neutral conditions, ambient turbulence, rather than thermal stratification, limits the rise by breaking up the plume. The final rise in this case is the level at which the internal turbulent dissipation rate of the plume matches the ambient turbulent dissipation rate. Equating these quantities, Brigg's (1984) specifies the final rise as

$$\Delta h_f = 0.76 \left(\frac{r_o U^2}{F^2 K^3 u_*^2} \right) \quad (6)$$

where u_* is the friction velocity (m/s).

In unstable conditions, plume rise is also limited by turbulence. Here, however, the turbulent dissipation of the downdrafts is equated with the plume dissipation rate since downdrafts are responsible for bringing elevated material to ground level. Under this premise Briggs (1984) and Weil (1987) suggest

$$\Delta h_f = 4.5 \left(\frac{r_o U^2 z_i^2}{4 F^2 K^3 w_*^2} \right)^{3/5} \quad (7)$$

where z_i is the inversion height [m] and w_* is the convective velocity scale [m/s].

In practice, the neutral plume rise relationship serves as a limiting case within our framework since both the stable and unstable limiting rise relationships go to infinity as neutral conditions are approached. We use the lesser of the stable or unstable final rise estimate (which ever is applicable) and the neutral estimate. Therefore, in unstable conditions the final rise is given by:

$$\Delta h_f = \min \{ \Delta h_f [\text{Eq. (7)}], \Delta h_f [\text{Eq. (6)}] \},$$

whereas for stable conditions

$$\Delta h_f = \min \{ \Delta h_f [\text{Eq. (5)}], \Delta h_f [\text{Eq. (6)}] \}$$

As previously discussed, a puff dispersion post processor is used to translate the vertical dispersion estimates from the Lagrangian model to a ground level concentration field from a time varying source. The puff dis-

persion model is constructed in a standard manner. The release is broken up into a series of 2-dimensional Gaussian puffs [i.e., $(x,y,z = 0)$] that are released on a certain time interval (typically 10 s. to 1 min.). Each puff is advected downwind while growing in lateral and streamwise directions. The concentration at a particular point at a particular time $C(x,y,t)$ is provided by summing the contributions from all the puffs such that

$$C(x, y, t) = \sum_{i=1}^N \frac{M_i}{(2\pi)^{3/2} \sigma_{xi} \sigma_{yi} \sigma_{zi}} \exp\left[-\left(\frac{y-y_o}{\sqrt{2}\sigma_{yi}}\right)^2\right] \exp\left[-\left(\frac{x-U(t-t_i)}{\sqrt{2}\sigma_{xi}}\right)^2\right] \quad (8)$$

where N is the number of puffs; and M_i , σ_{xi} , σ_{yi} , σ_{zi} and t_i are the mass, plume spread parameters and release times for each puff i . The σ_z values in Eq. (8) come directly from the MCLDM simulations. Here, σ_z is not the true σ_z as determined from the vertical concentration distribution, but is rather a fitting parameter that when inserted in the puff dispersion model will provide the correct ground-level crosswind integrated concentration. The σ_z relationship for each puff corresponds to the buoyancy for that puff. In the puff model, we assume transverse and streamwise diffusion of the puffs are equal (i.e., $\sigma_x = \sigma_y$). The horizontal plume spread parameters are estimated using the relationships by Draxler (1976) for stable conditions and Weil (1988, Eq. 4.61) for unstable conditions. Enhancement of σ_y due to buoyancy effects is neglected. For the applications considered with FIREPLUME to this point, this is an adequate approximation. However, for extension to wildland fires and prescribed burns, enhancement of σ_y due to buoyancy effects might be important and can be easily added to the model.

As discussed previously, both SMOKE and FIREPLUME originate from a common stochastic modeling framework embodied in MCLDM. However, in SMOKE, MCLDM dispersion estimates have been parameterized into a semi-empirical integral model that provides the crosswind integrated concentration as a function of time from release. This integral model is applicable to a full range of meteorological conditions but is limited by the fact that it does not treat source buoyancy. A description of this model is beyond the scope of this paper, but is contained in Brown (1997). The puff framework used within SMOKE is similar to that illustrated above in Eq. (8), except that puffs are advected randomly using a Langevin type equation, similar to Eq. (2). In doing this, the growth rate of the

puffs is set such that correct the plume spread is captured.

The puff dispersion framework allows treatment of many aspects of the obscurant release problem that is directly applicable to the prescribed burn problem. The most obvious of these is the ease at which puff models treat multiple, time varying sources which may also be moving. In addition, the puff framework allows SMOKE to adequately treat releases of short duration and allows the effects of temporal changes in meteorology to be properly modeled. Besides these intrinsic attributes, the puff framework in SMOKE provides for the convenient treatment of deposition and terrain effects, which are discussed below.

In the SMOKE model, deposition is treated using a deposition velocity formulation. Here, the deposition flux is given by

$$F_d(x, y) = v_d C(x, y, z)|_{z=0}, \quad (9)$$

where $F_d(x, y)$ is the deposition flux [$\text{kg m}^{-2} \text{s}^{-1}$], $C(x, y, z)|_{z=0}$ is the ground-level concentration (kg m^{-3}) and v_d is the deposition velocity [m s^{-1}]. The deposition calculation centers around estimation of the deposition velocity, which depends on many factors such as particle size, meteorology and surface characteristics. The deposition velocity model employed in SMOKE is based on the Urban Airshed Model (UAM; Gray 1991) with a modification suggested by EPA (1994). The UAM deposition model as modified by EPA was the best performer in terms of average deposition velocity in a detailed review of several state-of-the-art dry deposition models that can be applied with routinely available landcover and meteorological data.

Terrain effects are currently treated using a combination of two physical models for puff motion. The first is simple in that it does not allow the puffs to intersect with terrain features, forcing puffs to preferentially go around obstacles unless the obstacle is smaller than the puff itself. The second adjusts the puffs advection velocity based on surface slope and atmospheric stability. In unstable meteorology with strong surface heating, puffs will preferentially travel upslope. In contrast, during stable conditions with surface cooling, puffs will preferentially travel downslope. The stability dependent terrain component is added to the mean local wind speed so that they become relatively unimportant in the presence of a strong synoptic forcing flow.

DISTINGUISHING CAPABILITIES AND MODEL LIMITATIONS

The strengths of a proposed SMOKE-FIREPLUME modeling system (see discussion below) are its advanced treatments of vertical dispersion, its inclusion of RSC buoyancy effects, and its ability to address all fire release conditions, flaming, glowing, and smoldering. The system is capable of simulating smoke dispersion over complex terrain, and relies on state-of-the-science methods for particle/vapor cloud dispersion estimation. In addition, its PC-based format is particularly well suited to in-field or “real-time” smoke management or wildfire emergency response applications.

The modeling system is limited to local spatial scales starting at the fire front and extending downwind distances not exceeding about 10 to 50 km (or temporal scales less than 2 to 3 hrs). Also, model predictions have not been compared and evaluated with planned wildland fire field or laboratory measurements (Lazaro, et al. 1998).

HISTORICAL APPLICATIONS

Although the above referenced SMOKE-FIREPLUME modeling system has not yet been implemented and applied in practice, the models have been used individually in several consequence-exposure assessments for regulatory and/or training purposes. Two recent applications are highlighted below.

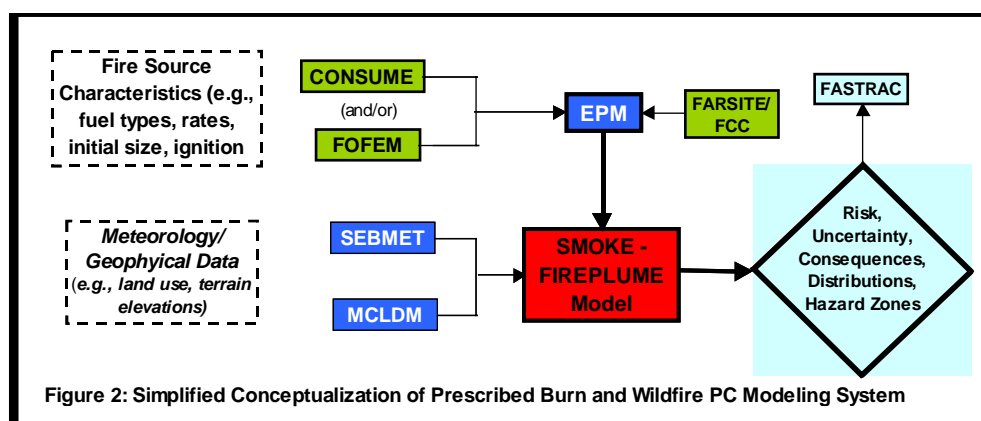
As previously noted, the first application of FIREPLUME involved the prediction of health impacts resulting from releases of uranium hexafluoride (UF_6) in fires in support of the Final Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted UF_6 (DOE/EIS-0269, <http://web.ead.anl.gov/uranium/finalpeis.cfm>). In this application, three phases of release and dispersion of UF_6 were treated. The first phase of release followed the hydraulic rupture of the cylinder due to heating of the uranium hexafluoride in the fire. In this phase, a large quantity of the UF_6 byproducts (UO_2F_2 and HF) were generated upon the emission of UF_6 and the reaction with water vapor in the air. This resulted in a slightly buoyant thermal. The second phase involved the emission of material into the burning fire resulting in buoyant plume type of release. The third phase involved the emission of material after the fire had died during the cool-down or smoldering period. This phase continued until the fire remnants cooled to the point where the release rate

of UF_6 byproducts was negligible. Human health end points relating to potential lethal and irreversible health effects were then used to quantify the impact areas from the ground-level concentration predictions. Altogether, three different fire scenarios were modeled with a variety of container configurations involving both large and small cylinders. Further details of the modeling effort are contained in (Brown, et al. 1996).

Another study involving FIREPLUME Model entailed the calculation of impacts downwind of accidental fires caused by lightning or weapons training exercises at Aberdeen Proving Ground. Emissions from those fires included both wood burning and some chemical agent re-emitted due to the fire. The FIREPLUME model simulated three phases of the emissions and predicted impacts both onsite and offsite from the proving grounds. The model predicted both plume rise and dispersion from the fire and smoke from which agent deposition and human health inhalation impacts were determined. The impacts due to a range of meteorological conditions were evaluated.

MEETING FUTURE SMOKE MANAGEMENT NEEDS

One of the “Air Quality Express” recommendations coming from the Forest Service’s National Strategic Plan for modeling air quality impacts from wildland fires was the development of a comprehensive smoke management system linking fire behavior, fuel consumption, emissions, and dispersion models. Emphasis is placed on the need for developing a user friendly system that accurately represents the full array of fuel types and conditions. A desire was indicated for model outputs that could be integrated across all spatial scales. A simple conceptualization of how a comprehensive smoke management system might look is depicted in Figure 2. Although the proposed modeling framework is built around a PC based tool (i.e., the SMOKE-FIREPLUME model air dispersion model, for event to landscape applications), more complicated regional or continental scale air dispersion models could be selected dependent on end-user needs. The integrated system depends on important parameter outputs from established and developing fuel consumption/ behavior and emission models. With the exception of CONSUME, none of these models are currently capable of addressing smoldering and/or glowing combustion effects. The fuel consumption algorithm in CONSUME is currently being upgraded to improve its simulations of smoldering combustion. New fuel consumption algorithms are being added to extend the model to national scale applications. The Emission Production



Model (EPM) is linked to CONSUME and is likewise currently being upgraded to address the smoldering source-term and initial plume dynamics. Other linkages from FCC (Fuel Characteristic Classes) and FARSITE (data layer development) to EPM are also being planned. These improved models/databases, especially in the RSC area, would provide valuable data (i.e., model outputs) on time varying emission rates for gases, particles, and heat. The data could be easily linked to the SMOKE-FIREPLUME model. Emissions, heat flux or temperature data, along with the necessary meteorology (e.g., winds, stability) would allow the simulation of smoldering plume dynamics (low- or non-buoyant effects that result in low-level ground hugging drift plumes) in estimating downwind prescribed burn or wildfire air quality impacts. As shown in Figure 2, the information coming from SMOKE-FIREPLUME could be fed to tools, such as FASTRAC, as an aid to smoke management decision support. As mentioned earlier, the SMOKE-FIREPLUME model is limited to fire applications for assessing local to mid-regional scale impacts (i.e., event to state/tribal ecological scales as defined in Sandberg, et al. 1999) from RSC smoke and toxic gas plumes. The desire for integration across multiple scales is possible but would require models of increasing complexity that might hinder the “Air Quality Express” team’s recommended goal of keeping the modeling system simple and user friendly.

Although currently capable of limited use in targeted risk management zones (e.g., prescribed burns in a small urban-wildland interface area), further model refinement and evaluation has been recommended before consideration of wider smoke management application (Lazaro, et al. 1998). The identified model and modeling system end-user enhancements and improved science needs include:

- Refinements to *smoldering/glowing and flaming plume* rise algorithms, accounting for temporal and spatial variations in plume buoyancy and further accounting for the effects of plume buoyancy on vertical and horizontal dispersion. The approach would depend upon the degree of success in incorporating the computation of spatially and temporally varying heat flux across varying fuel types within the EPM. Another approach would to consider incorporating the relevant fire stoichiometry and chemistry (primary exothermic reactions) for both flaming and non-flaming fuels into the SMOKE-FIREPLUME model.
- Improve the treatment of *Visibility impairment*, especially under residual smoldering and glowing combustion (slightly or neutrally buoyant plumes) in all fuel types (i.e., including deep organic layers). Both black and white wildland fire smoke will affect visual range degradation. The optical properties of black smoke generated during flaming combustion may absorb significant amounts of solar radiation while white smoke generated during smoldering combustion conditions is more reflective (e.g., higher albedo).
- *Comparison and evaluation of model performance* with data from prescribed burn field or laboratory experiments, for a range of fuels (i.e., evaluate fuel type influences, testing and validation).
- *Integration and linkage* with existing fire and smoke management tools and databases (e.g., EPM, CONSUME, BDB, WIMS-GOES, FETM). This would include refinement and adaptation of the existing graphical user interface within the SMOKE-FIREPLUME model, consistent with end-user needs (see Figure 3). Emphasis would

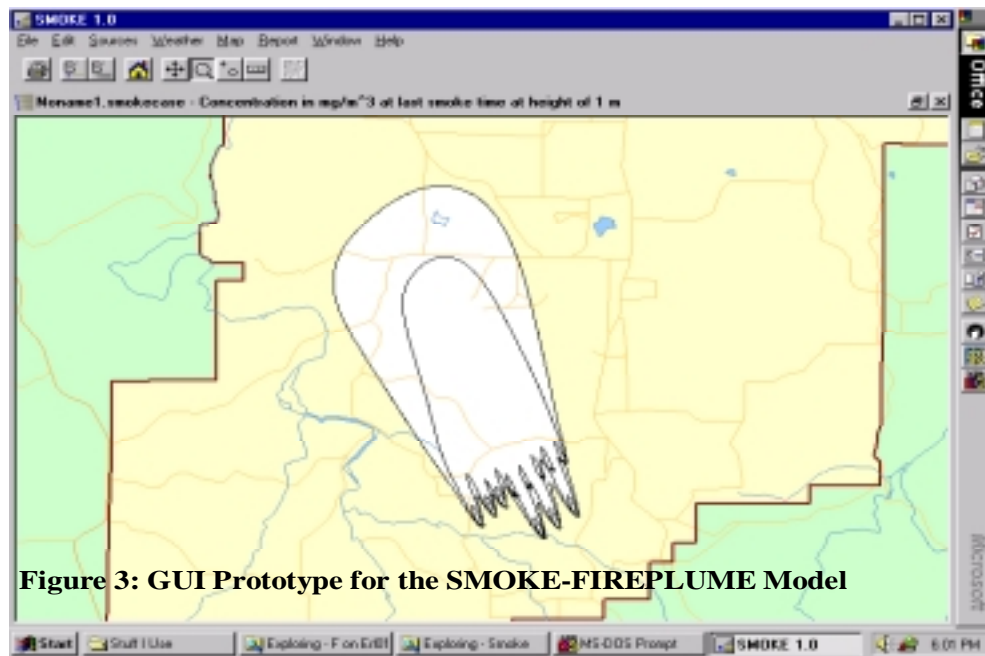


Figure 3: GUI Prototype for the SMOKE-FIREPLUME Model

be placed on providing model outputs that are user relevant and easy for air and land managers to understand.

- Make *real-time local weather* information available through the development of local meteorological data input to the consumption, emission and dispersion models when used in the field. This could include interface with data from existing instrumented (with necessary modification) small portable meteorological towers and/or connection to the nearest weather station.

An air modeling system as illustrated above could be valuable to land and air resource managers in planning, operating and monitoring wildfire land and smoke management activities and in implementing policy objectives. Such a system could aid in the planning, design and implementation of prescribed burns that minimize health and safety risks to firefighters and the public. Integration of real-time weather forecasts could further reduce these risks and help eliminate or significantly reduce property damage and nuisance complaints. The extent of air quality impacts computed before initiating a prescribed burn would be important to effective emergency response planning and plume trajectory forecasts would be valuable during a prescribed burn in alerting and/or notifying the public of potential smoke and fire danger. Since control and containment of smoke and toxic gases emanating from RSC may have significant local conse-

quences, the relative impacts of smoke emission reduction alternatives (e.g., target area concentration burning to reduce burn area, mechanical fuel removal to reduce fuel loading, helitorch burns to reduce fuel consumption) could be evaluated and used by land and resource managers in choosing alternative smoke management options.

REFERENCES

- Briggs, G. A. (1984). Plume Rise and Buoyancy Effects, in *Atmospheric Science and Power Production*, D. Randerson (ed.), DOE/TIC - 27601, Weather Service Nuclear Support Office, National Oceanic and Atmospheric Administration, United States Department of Commerce, 327-366.
- Brown, D. F., Dunn, W. E., A. J. Policastro, and D. Malony. (1996). FIREPLUME Model for Plume Dispersion from Fires: Applications to UF6 Cylinder Fires, ANL/EAD-PM69.
- Brown, D. F., Dunn, W. E. and A. J. Policastro. (1990). Analysis of Meteorological Data from the AMADEUS Smoke Dispersion Experiments, completed for the U. S. Army Biomedical Research and Development Laboratory under contract No. 90PP0819, University of Illinois, Urbana, IL.
- Brown, D. F. (1997). *An Improved Methodology for Characterizing Atmospheric Boundary Layer Turbulence and Dispersion*, Ph. D. Thesis, University of Illinois, Urbana, IL.

- Conrad S. G. and D. R. Weise's. (1998). Management of Fire Regime, Fuels and Fire Effects in Southern California Chaparral: Lessons from the Past and Thoughts for the Future, in the proceedings of *Tall Timbers Fire Ecology Conference*, No. 20.
- DeVaull, G. E., Brown, D. F., Dunn, W. E. and A. J. Policastro. (1990). "Fluctuating Concentrations in Atmospheric Dispersion," completed for the U. S. Army Biomedical Research and Development Laboratory, University of Illinois, Urbana, IL.
- DOI-DOA. (1995). Federal Wildland Policy and Program Review, BLM, Final Report, 45p, <http://www.fs.fed.us/land/wdfire.htm>.
- DOI-DOA. (1996). Federal Wildland Policy and Program Review: Implementation and Action Plan Report, BLM, Final Report, May, 40p, <http://www.fs.fed.us/land/wdiap.htm>.
- Draxler, R. R. (1976). Determination of Atmospheric Diffusion Parameters, *Atmospheric Environment*, 10, 99-105.
- EPA. (1994). Development and Testing of a Dry Deposition Algorithm (Revised), Report EPA-454/R-94-015, Environmental Protection Agency, Research Triangle Park, North Carolina.
- EPA. (1998). Interim Air Quality Policy on Wildland and Prescribed Fires, May 15.
- Gray, H. A., et al. (1991). Deterministic Modeling in the Navajo Generating Station Visibility Study: Volume 2. Systems Applications International Corporation, San Rafael, California.
- Hilbruner, M. (1999). Personal communications, Forest Service, Washington, D. C., July 30.
- Kaimal, J. C. and J. J. Finnigan. (1994). *Atmospheric Boundary Layer Flows*. Oxford University Press, New York.
- Keeley, J. E., Fotheringham, C. J., and M. Morais. (1999). Reexamining Fire Suppression Impacts on Brushland Fire Regimes, *Science*, 284, June 11, 1829-1832.
- GCVTC. (1996). Proposed Recommendations of the Grand Canyon Visibility Transport Commission, Public Advisory committee, Final report, May.
- Lazaro, M. A., Brown, D. F., Dunn, W. E., and A. J. Policastro. (1998). Integrated Smoke Biomass Generation and Dispersion Modeling System — Development and Evaluation — A pre-proposal for submittal to the Joint Fire Science Program, July.
- Ley, A. J. (1982). A Random Walk Simulation of Two-Dimensional Turbulent Diffusion in the Neutral Surface Layer, *Atmospheric Environment*, 16, 2799-2808.
- Liljegren, J. C., Dunn, W. E., DeVaull, G. E. and A. J. Policastro. (1989). The Atterbury-87 Field Study of Smoke Dispersion and a New Stochastic Dispersion Model, completed for the U. S. Army Biomedical Research and Development Laboratory, University of Illinois, Urbana, IL.
- McKenzie, L., Hao, W. M., Richards, G., and D. Ward. (1995). Measurement and Modeling of Air Toxins from Smoldering Combustion of Biomass, *Environ. Sci. Tech.*, 29(8): 2047-2054.
- Reid, J. D. (1979). Markov Chain Simulations of Vertical Dispersion in the Neutral Surface Layer for Surface and Elevated Releases, *Boundary-Layer Meteorology*, 16, 3-22.
- Sandberg, D., Hardy, C., Ottmer, R., J. Shell, Acheson, L., Peterson, J., Seamon, P., Lahm, P. and D. Wade. (1999). National Strategic Plan: Modeling and Data Systems for Wildland Fire and Air Quality, PNW-GTR-450, Feb.
- Thomson, D. J. (1984). Random Walk Modelling of Diffusion in Inhomogeneous Turbulence, *Quarterly Journal of the Royal Meteorological Society*, 110, 1107-1120.
- Thomson, D. J. (1987). Criteria for the Selection of Stochastic Models of Particle Trajectories in Turbulent Flows, *Journal of Fluid Mechanics*, 180, 529-556.
- van Dop, H., F. T. M. Nieuwstadt and J. C. R. Hunt. (1985). Random Walk Models for Particle Displacements in Homogeneous Unsteady Turbulent Flows, *Physical Fluids*, 28, 1639-1653.
- Ward, D. E., Hardy, C. C., Sandberg, D. V. (1988). Emissions Factors for Particulates from Prescribed Fires by Region in the United States, Proc. of the Air Pollution Control Assoc./EPA Specialty Conf.
- Weil, J. C. (1982). Source Buoyancy Effects in Boundary Layer Diffusion, in *Workshop on the Parameterization of Mixed Layer Diffusion*, R. Cionco (ed.), Physical Sciences Laboratory, New Mexico State University, Las Cruces NM.
- Weil, J. C. (1988). Plume Rise, in *Lectures on Air Pollution Modeling*, A. Venkatram and J. C. Wyngaard (eds.), American Meteorological Society, Boston, 119-157.

Willis, G. E. and J. W. Deardorff. (1974). A Laboratory Model of the Unstable Planetary Boundary Layer, *Journal of Atmospheric Sciences*, 31, 1297-1307.

Woodard, K. (1999). Personal communications, U. S. EPA, OAQPS, RTP, July.

WRAP. (1999). Work Plan of the Western Regional Air Partnership, Fire Emissions Joint Forum, February 11.

Yokelson, R. J., Goode, J., Ward, D., Baker, S., Susott, R., and W. M. Hao. (1999). The Chemistry of Fire and Smoke: Composition, Amount, and Fate of Smoke from Residual Smoldering Combustion, *Published in these proceedings*.

Yokelson, R. J., Susott, R., Ward, D. E., Reardon, J., and D. W. T. Griffith. (1997a). Emissions from Smoldering Combustion of Biomass Measured by Open-path Fourier Transform Infrared Spectroscopy, *J. Geophys. Res.*, 102 (D15), 18,865-18,877.

Yokelson, R. J., et al. (1997b). START Synthesis Workshop on Greenhouse Gas Emission, Aerosols and Land Use and Cover Changes in Southeast Asia, 15-18 Nov., Taipei.